AgIIS, Agricultural Irrigation Imaging System

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Abstract. *AgIIS (Agricultural Irrigation Imaging System, pronounced Ag Eyes), a ground-based remote sensing system, served as a research tool that generated data for research on remotely sensed canopy level water and nitrogen status indices. A rail was mounted on a 100-m long linear move irrigation machine, and a cart with a remote sensing unit ran back and forth on the rail. As the cart traveled along the rail and the linear move traveled through the field, the sensing unit collected one square meter area reflectance measurements every meter along the rail. Because the system was automated, the remotely sensed data was acquired with low labor cost compared to traditional handheld radiometers, and provided high temporal and spatial resolution. The system monitored a 0.5-ha research area with 16 research plots.*

The rail, made of steel tubing, was constructed of three parallel tubes in a triangular frame. The rail had almost no vertical deflection due to cart weight, and slip joints between sections were elastic enough to absorb the deformation of the linear move when loaded with water.

The sensor package included four reflectance bands filtered to narrow wavelength intervals (10 nm) in the red (670 nm), green (555 nm), red-edge (720 nm), and near infrared (NIR) (790 nm) portions of the spectrum, and an infrared thermometer.

The crop spectral signals were post-processed in order to construct georeferenced field maps of vegetation, nutrient, and water status indices. Analysis of the data showed that the rail and cart provided a platform for collection of consistent and reliable remote sensing data, and it served as a valuable tool for refinement of water and nitrogen status indices. The AgIIS design effectively and reliably collected remote sensing data from a constant elevation, at near nadir orientation, and at 1-m intervals.

Keywords. *Remote sensing, Irrigation, Center pivot, Linear move, Ndvi, Cwsi, Ccci.*

AgIIS (Agricultural Irrigation Imaging System, pronounced Ag Eyes), was a ground-based remote sensing research tool that was installed on a 100 m long linear move irrigation machine and covered a 0.54 ha research area with 16 plots that were 20 × 20 m. It was developed by and used in a collaborative effort by the University of Arizona and the USDA-ARS Arid Lands Agricultural Research Center and was located at the University of Arizona's Maricopa Agricultural Research Center near Phoenix, Arizona. The AgIIS system included a rail mounted on the linear move and a cart equipped with remote sensing equipment that ran back and forth along the rail. The radiometer on the cart included four reflectance bands filtered to narrow wavelength intervals (10 nm) in the red (670 nm), green (555 nm), red-edge (720 nm), and near infrared (NIR) (790 nm) portions of the spectrum, and an infrared thermometer. Remotely sensed data was collected at a spatial resolution of 1 m^2. The crop spectral signals were post-processed in order to construct georeferenced field maps of vegetation, nutrient, and water status indices. Researchers used the AgIIS data to develop or refine nitrogen and water status indices for cotton and broccoli.

Remote sensing indices have been developed that measure plant water status (Jackson et al., 1981; Idso, 1982; Jackson, 1982), and vegetation density (Deering, 1978; Tucker, 1979, Heilman et al., 1982; Huete, 1988; Jackson and Huete, 1991). The red (670 nm) and near infrared (790 nm) bands in the AgIIS radiometer were used to measure vegetation indices such as the normalized difference vegetation index (NDVI). The AgIIS infrared thermometer (IRT) measured crop temperature and was used along with the NDVI to evaluate the water deficit index (Colaizzi et al, 2002a; Colaizzi et al., 2002b, El Sheikha et al., 2007, El Sheikha et al., 2008). The red (670), red edge (720), and NIR (790) bands in the AgIIS system were used by the research team to develop the canopy chlorophyll content index (CCCI), which measures the nitrogen status of plants (Barnes et al., 2000; Kostrewski et al., 2003; El Sheikha et al., 2007; El Sheikha et al., 2008).

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Materials and Methods

The AgIIS system components included the rail, cart, and data acquisition system. As the cart traveled along the rail and the linear irrigation system moved through the field, reflectance measurements were collected every meter. These measurements were georeferenced and later post-processed in order to develop remote sensing index maps of the field.

Rail

Because AgIIS was used as a research instrument, minimal deflection and maximum stability of the rail was a design goal in order to keep the sensor at nadir angle and to maintain uniform cart speed.

The triangular rail (fig. 1) was constructed in 6-m long spans composed of three mild steel tubes (C1020 AISI), 25.4-mm OD, and 1.25-mm wall thickness. The three tubes were welded together by triangular braces forming a 250-mm equilateral triangle. The braces were made out of 19-mm mild steel tubing and were uniformly spaced at 1.5 m along the rail forming a composite beam. The rail was supported every 3 m along the linear move irrigation pipeline (fig. 1) by a support arm that was attached to the linear move pipeline with a U-bolt.

The vertical deflection of the rail with the cart (40 kg) located half way between supports was calculated for a point load on a composite triangular beam with three tubes. The moment of inertia for each tube was:

$$I_t = \frac{\pi\left(d_1^4 - d_2^4\right)}{64} = 6.9 \times 10^{-9}\ m^4 \tag{1}$$

where
I_t = moment of inertia for one tube (m^4)
d_1 = outside diameter (0.0254 m)
d_2 = inside diameter (0.0229 m)

The centroid of the composite beam, an equilateral triangle was:

$$c_b = 0.66h = 0.66 \times 0.22 = 0.15\ m \tag{2}$$

where
c_b = centroid of composite beam (m)
h = height of the triangular composite beam (0.220 m)

The moment of inertia of the composite beam was calculated with the parallel axis theorem:

$$I = A_t(c_b^2 + 2(h - c_b)^2) + 3I_t = 3.1 \times 10^{-6}\ m^4 \tag{3}$$

where
A_t = area of the tubing cross section (9.5×10^{-5} m^2)

The mass of the cart was 40 kg; thus, the point load was 390 N and the expected deflection of the composite beam under this load with a 3-m distance between supports was:

$$\Delta = \frac{PL^3}{48EI} = 3.5 \times 10^{-4}\ m = 0.35\ mm \tag{4}$$

where
Δ = deflection (m)
L = distance between rail supports (3 m)
P = point load acting on the beam (N)
E = modulus of elasticity for steel (2.068×10^{11} N-m^2)

In order to provide the longitudinal elasticity required for mounting the rail on a flexing linear move irrigation system, the joints between spans matched the shape of the triangular braces but slipped along the inside of the rail tubes and allowed for rail expansion and contraction. At the point where the linear move spans connect, angular deflection

Figure 1. AgIIS rail.

occurs as the machine "walks" with variable tower positions through the field: a flexible slip joint was constructed with a steel spring (fig. 2) that allowed for angular deflection.

Two 16.0-mm OD copper tubes were mounted on top of the rail to conduct electricity along the rail. The copper tubes were mounted on rubber insulators and were joined together with slip connectors that were similar to the slip connectors used on the main rail tubes.

The mass of the rail, including the copper conductors, steel tubing, and braces, was 4.6 kg per linear meter of rail. Originally, the rail was hung 1 m off center on the west side of the linear move in order to extend the sensor field of view beyond the linear move pipeline suspension system and support braces. The offset of the rail system with respect to the longitudinal center of the linear move produced a moment on the irrigation machine that was counterbalanced with weights on the east side of the machine. Because the moment was not perfectly offset by the weights and because the weights added extra stress on the irrigation machine, the rail was disassembled and reinstalled directly on top of the irrigation pipeline. An extended arm was attached to the cart in order to extend the sensor view away from the structure of the linear move.

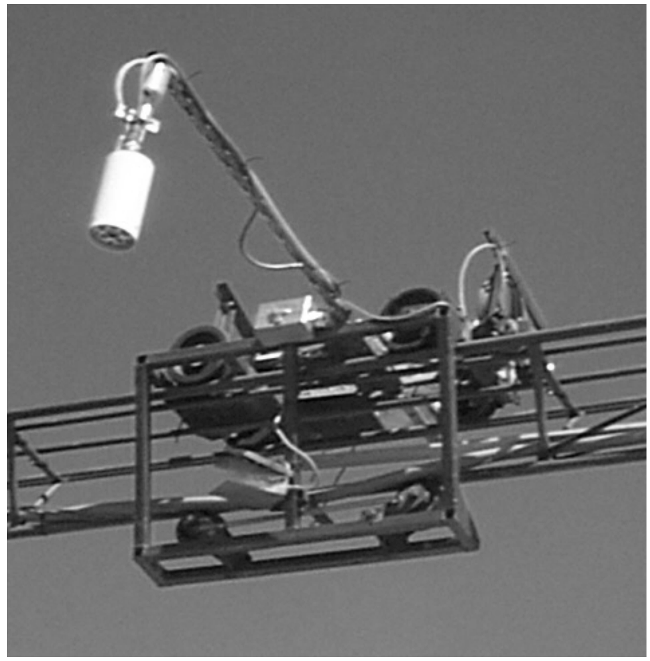

Figure 3. AgIIS cart, arm, and sensor.

Cart and Data Acquisition

The cart was constructed from 25.4-mm mild square steel tubing (C1020 AISI), 2-mm wall thickness. It had a total of six wheels with two wheels riding along each of the three rail tubes (fig. 3). Each of the six hard rubber wheels had a semicircular groove in order to allow the cart to roll along the circular tubes of the rail. The wheels running on the upper tubes of the rail were 154 mm in diameter but the effective diameter (bottom of groove) was 130 mm. The two bottom wheels were 100 mm (75-mm effective diameter) and were spring loaded so as to clamp the cart to the rails, ensuring that it would not derail. The sensor was extended on an arm to the west of the cart and linear move. Thus, data was collected beginning at solar noon.

Sensors were triggered and data was collected with a Campbell Scientific CR-10X data logger (Logan, Utah), which includes a measurement and control module, external power supply, and keyboard display. Because data were acquired at 1-m intervals, and the acquisition and processing time per measurement was roughly 0.5 s, the maximum possible cart speed was 2 m-s^{-1}. It was thought that a 3-h window (11:00 to 14:00 h with solar noon at 12:30) was the maximum amount of time that should be used to scan the field. Thus, a cart velocity of 1.2 m-s^{-1} was chosen. The diameter of the bottom of groove on the wheels, D, was 130 mm so the required wheel rpm was:

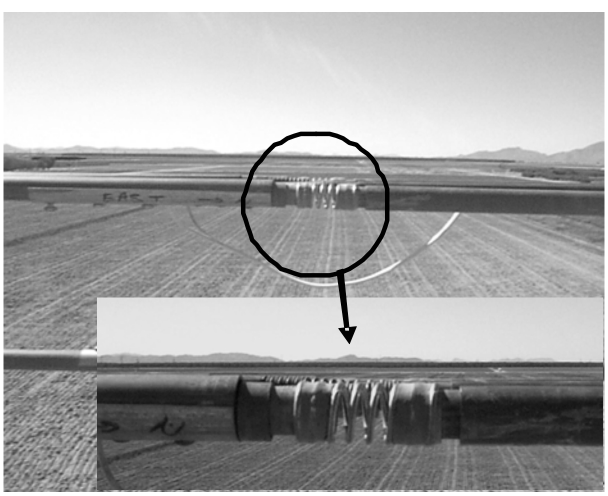

Figure 2. Flex joint at connection point between linear move spans.

$$rpm = 60\frac{v}{\pi D} = 176\ rpm \qquad (5)$$

where

v = cart velocity (m-s^{-1})

D = wheel diameter (m)

The cart was powered by a 90-V DC gear motor (model 1L500, Dayton Motor, Dayton, Ohio), that exerted 0.25 hp at 1800 rpm. The Dayton gearbox had a ratio of 10:1 and ran the wheels at 180 rpm; thus, the cart had a maximum speed of 1.2 m/s. Power was obtained from a 120-V AC source that was rectified to 90 V DC on the copper rails by a Dayton variable 0- to 90-V AC/DC rectifier. The variable voltage, supplied to the rails and ultimately the motor through copper contact wheels, controlled the speed of the cart. The direction of run was controlled by the polarity of the power supplied to the motor. Two switches, one at each end of the rail, activated a relay system that reversed the polarity in the copper rails.

The length of the rail was 100 m; thus, the cart travel time from one end of the rail to the other was 83 s. The cart accelerated to full speed within 1 m. The rail electronics were designed to stop the cart for 3 s at each end in order to clearly show the time in the data at which the cart changed direction; thus, the total travel time in each direction was 86 s. The linear move was programmed to travel 1 m in 86 s or 0.70 m min^{-1} so the cart returned to the starting point every time that the linear move traveled 2 m. At 0.70 m min^{-1}, the linear traversed the 100-m long field in 2 h and 20 min.

The remote sensing optics and electronics were designed and constructed at the USDA-ARS Arid Lands Agricultural Research Center (ALARC) in Phoenix, Arizona. It included four silicon detectors from Ealing Electro Optics filtered to narrow wavelength intervals (~10 nm) in the red (670 nm), green (555 nm), red-edge (720 nm), and near infrared (790 nm) portions of the spectrum, and an infrared thermal band (Barnes et al., 2000). The reflective bands were calibrated to units of reflectance by taking the ratio of downward looking sensor mV readings to mV readings from upward-looking sensors measuring the same spectral bands. Sensors were calibrated with a reflectance panel on the ground surface.

Tilt of the cart and sensor was caused by imperfections in the rail and movements of the irrigation system. A gimbal was installed to minimize the tilt of the sensing unit and keep the sensors perpendicular to the crop canopy (fig. 4). The gimbal was fabricated and included a stainless steel ball that was fixed in place between two Teflon disks; it proved to be effective as it reduced angular deflection from ±10° to ±3°. A bi-axial clinometer recorded the tilt of the sensor head in both the N-S S and E-W directions to determine variations from nadir view angle.

The CR-10X was triggered with an optical proximity sensor at each 1-m wide crop row; a small cable ran the length of the rail, and metal strips attached to the cable were aligned with each row. Six readings from each of the five downward looking sensors were averaged over each crop row with a burst measurement by the CR-10.

Two different approaches were used to record the position of the cart. The second approach is described in the following paragraph. The first method recorded the E-W position of the linear move with a Trimble AgGPS 132, 12-channel receiver (Sunnyvale, Calif.) that was mounted at the south end of the linear move from 1999 to 2001. Data was stored in a Harvestmaster Pro 2000 data logger (Juniper Systems, Logan, Utah). The workable sensitivity of the Trimble GPS receiver was 1 m. The E-W position (fig. 5) of the linear move was recorded by the GPS, and the N-S position of the cart was determined by the number of readings after the 3-s cart delay at each end of the rail. The CR-10X, Harvestmaster Pro data logger, and a CR-10X that recorded data from an upward looking solar irradiance sensor on the ground were time synchronized in order to correlate reflectance measurements with position data. A Visual Basic computer program integrated the data sets.

The angle of the two span linear move remained perpendicular to the path of travel; there was no observable lag at the end of the linear move as it progressed through the plots. Thus the GPS receiver location at the linear move cart was representative of the EW location of the entire linear move. However, in order to minimize error due to possible misalignment of the linear move, the Trimble AgGPS114 was placed on the cart in 2001 order to improve position data, and the upward looking solar irradiance sensor, and Campbell Scientific humidity and temperature sensors, were added to the cart in order to detect microclimate changes over the field. Data from the additional sensors and GPS unit were all recorded on the CR-10X data logger mounted on the cart.

Approximately 10,000 data points were collected during the period that the linear/cart system traversed the entire field each day. Data from the Campbell Scientific data logger was converted to a georeferenced remotely sensed indice database image map with a Visual Basic program. For each data point the program provided an approximate latitude, longitude, corrected sensor reflectance values, canopy temperature, and four vegetative indices. The AgIIS cart traveled through the field in a triangular pattern and a square grid pattern was constructed based on least squares interpolation between the raw data points.

The entire field was 72 × 76 m, and research plots were 22 × 22 m with rows in the E-W direction (fig. 5). Access paths were approximately 1.85 m in the N-S direction and 3.15 m in the E-W direction. Useful remotely sensed data collected in plots was separated from data collected from access paths and edge effect rows. Pathway center lines were determined with the Trimble AgGPS114. Masks were applied to the data in order to remove all data in pathways and edge effect zones. The standard deviation of GPS readings was 0.76 m (Kostrewski et al., 2003). Based on this variation and to remove edge effects, only 20 × 20 m within the centers of plots was used for data analysis. The mask removed the paths + 1.3-m data from the edges of plots: 1-m row of cotton plants +0.3 m to compensate for the standard deviation of

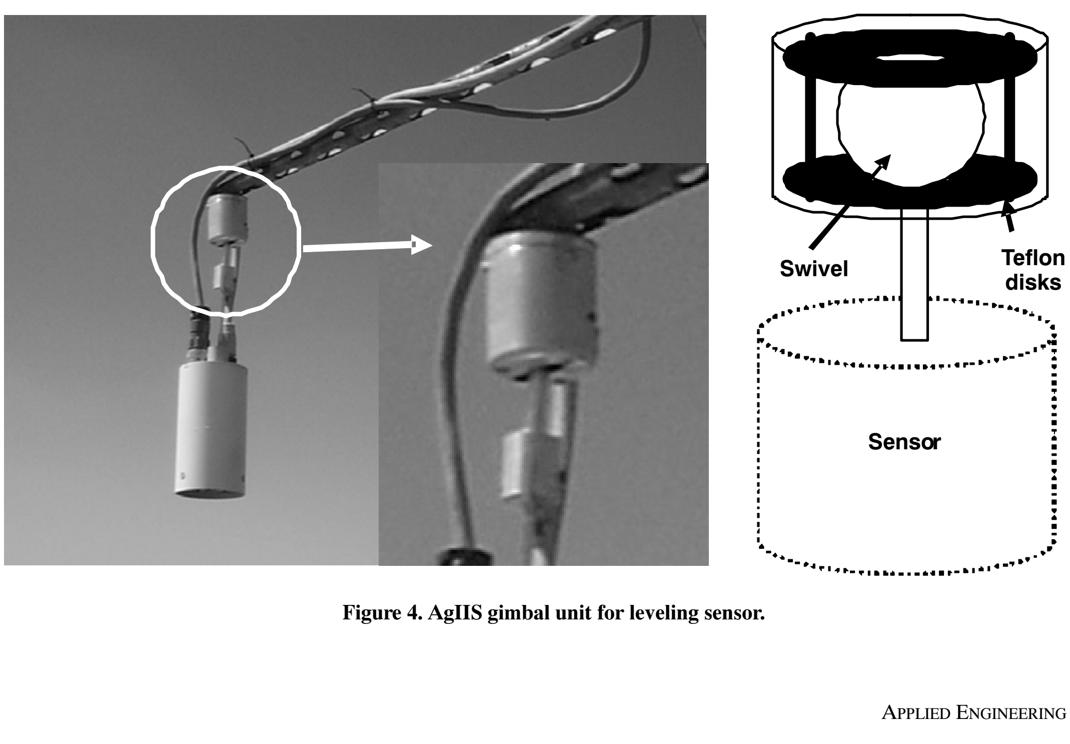

Figure 4. AgIIS gimbal unit for leveling sensor.

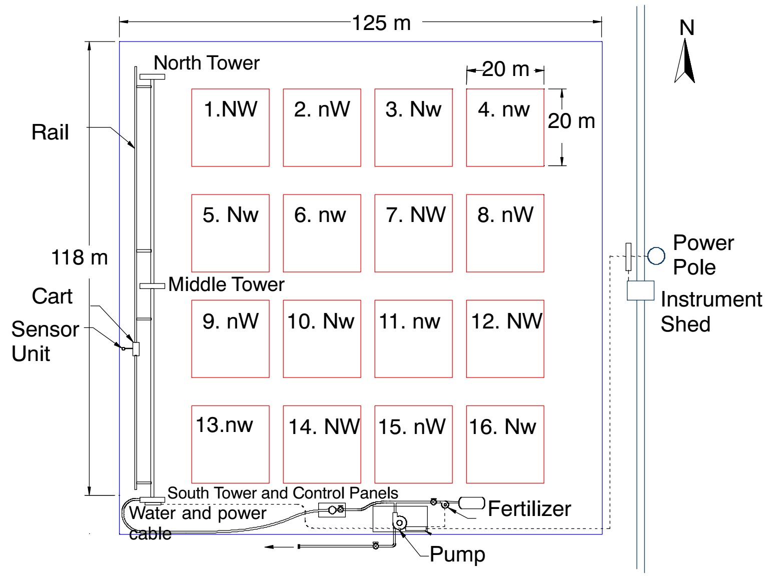

Figure 5. Schematic of Agricultural Irrigation Imaging System (AgIIS) and field layout. Plot numbers shown in blocks, with optimal treatments for water and nitrogen designated as capital N & W and stressed treatments as lower case. Not to scale.

GPS readings. Thus, there were 400 usable data points in each of the 16 plots (20 × 20 m) for a total of 6,400 usable data points in the entire experimental area.

Results and Discussion

A typical AgIIS map of the experimental area is shown in figure 6. Forty sets of images of the research area were compiled during the 1999 cotton growing season. Twenty six sets of images of the ratio vegetation index (RVI), canopy chlorophyll content index (CCCI), and the crop water stress index (CWSI) are presented in figure 7. In the RVI images it is possible to observe the changes in vegetation over the season: yellow represents bare soil, a gradient between green and blue shows actively growing vegetation, while reddish tones represent low vegetation density or senescing vegetation. Similar gradual changes are observed in the CCCI and CWSI images.

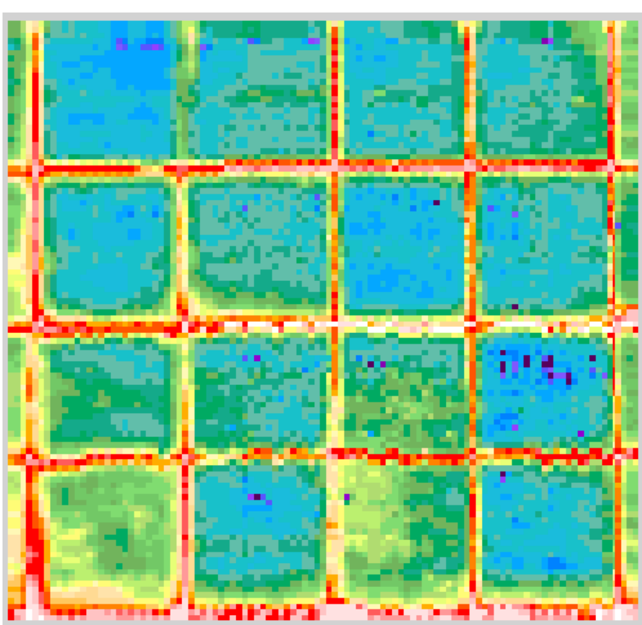

Figure 6. Ratio vegetation index image of AgIIS field (DOY 238, 1999).

One of the advantages of the AgIIS system is that the spatial variability of plots (fig. 6) can be viewed. A drawback, however, is that the apparent statistical deviation is less than the actual deviation in the images because each of the points in a square grid is calculated with a least squares algorithm based on the raw AgIIS data which was not collected on a square grid.

The initial plan was to collect AgIIS data from 11 a.m. to 2 p.m. However, data could not be collected before solar noon (12:30 p.m.) due to shadowing by the linear move. Thus, during the 1999 cotton experiment, half field readings were collected from DOY 165 to DOY 197 because it was thought that the solar angle after 2 p.m. would change the reflectance readings. However, midway through the season, it was determined that readings taken from 2 p.m. to 3:30 p.m. were not different from those collected before 2 p.m. This determination was made by comparing half field readings collected on Monday, Tuesday, Thursday, and Friday with complete field measurements collected on Wednesday. During the entire field data collection on Wednesdays, the solar zenith angle approached 32° at the end of the measurement period. Nevertheless, there was not an observable difference between measurements taken on Wednesdays and on the other days of the week. Thus, the system was used to collect data from the entire field for the rest of the season from solar noon (12:30 p.m.) to approximately 3:30 p.m. without a significant change in reflectance or thermal indices due to solar angle.

The rail provided a stable platform for the cart with good torsional and vertical stability. The cart traveled at a uniform speed along the rail and was able to effectively collect remote sensing data. The gimbal kept the sensor within ±3° of nadir. Without the gimbal, the tilt range was ±10°.

There was very little expansion and contraction of the linear move system. Thus, if a future system is constructed, the slip joints between each section may not be necessary. On

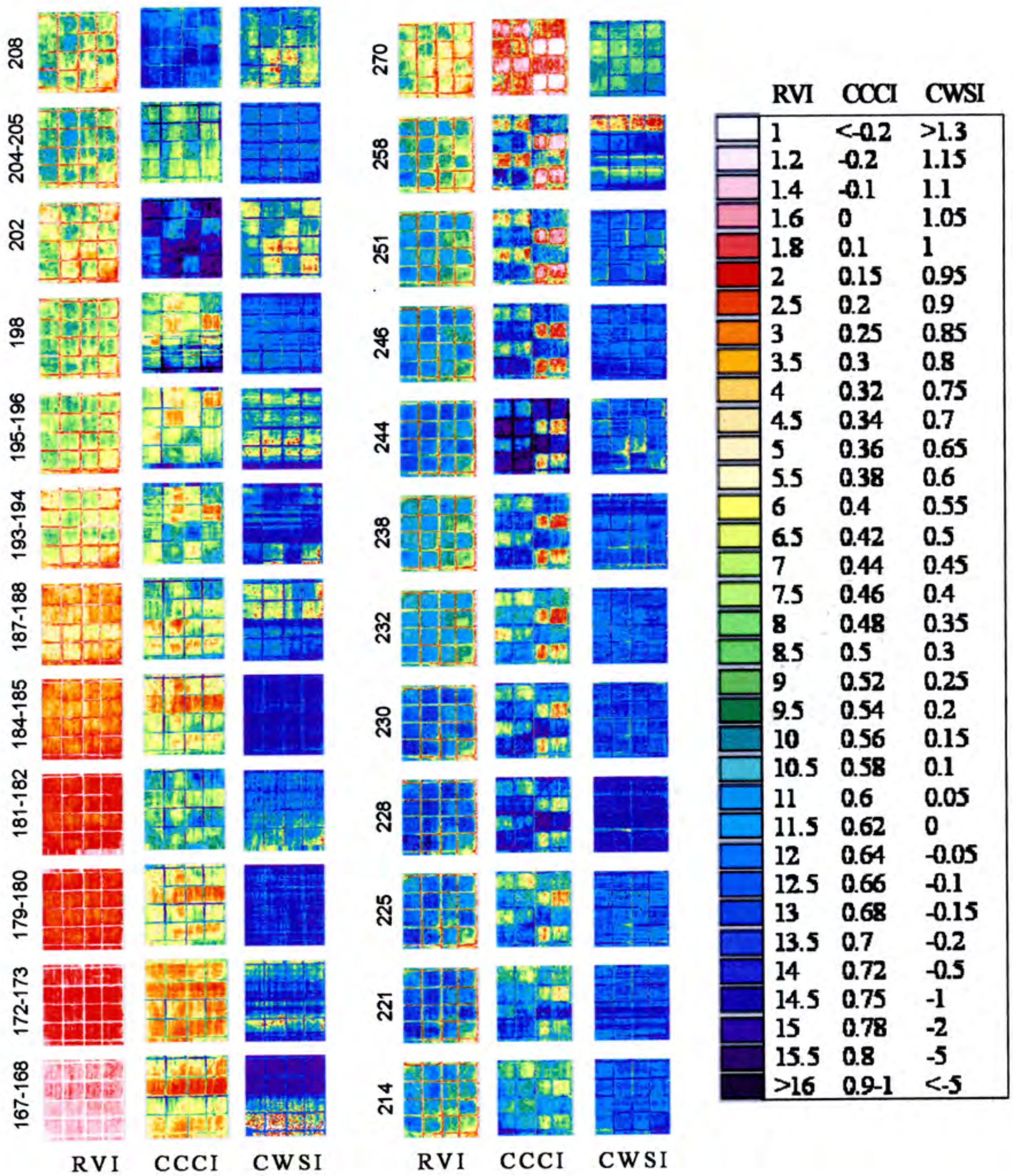

Figure 7. Sequence of RVI, CCCI, and CWSI maps composed from AgIIS data for cotton from DOY 167 to DOY 278.

the level field at Maricopa Agricultural Center, it is also likely that the spring connection joints at the junction between linear move spans that allowed for bending between spans were unnecessary.

The system was adequate for the 0.54-ha research area. It is possible that a larger area could be monitored with an AgIIS system attached to a center pivot. The fact that a center pivot changes angular direction could be used to advantage and allow collection of data from approximately 9:30 a.m. to 3:30 p.m. If a center pivot on a 24-h counter clockwise rotation pointed north at 6 a.m., pointed west at 12 noon, and south at 6 p.m., and if the sensor was placed on the leading side of the linear move, then it would be on the sunny side of the linear move during the entire day.

A lighter rail system would be easier to construct. Although the cart motor worked consistently and provided a reliable source of power for cart movement, it added a significant weight to the cart and necessitated the heavier cart and rail design.

The insulated connectors that joined the copper tube conductors to the rail broke several times during the summer due to expansion and contraction of the rail and tubes and needed to be replaced.

The cost of construction of the AgIIS rail and cart system (excluding the cost of the linear move) was approximately $35,000 for a 100-m long rail and cart system. The cost of the rail was approximately $100/m ($10,000 for 100 m) with half of the cost as skilled labor (welding and machining) for construction of prototype systems. The cost of electrical components was $3,500 with over 1/3 of the cost as labor. The cost of the cart was $2,500 with over half of the cost as labor. The remainder of the $35,000 cost included data loggers, weather station, computer and telemetry system, shipping, and the sensor package.

The 40 days worth of remotely sensed data provided extensive opportunity for calibration of remotely sensed indices (fig. 7). If an airplane was hired to monitor the field on 40 days, then the cost of just the pilot and plane for 40 days of equivalent high-resolution remotely sensed data would be approximately $40,000.

Unfortunately, the linear move that held the AgIIS system blew over in an Arizona summer monsoon. The surviving parts of the AgIIS system were moved to a greenhouse for monitoring greenhouse plants.

Conclusions

As a research tool, the AgIIS system proved to be very valuable. The strengths of AgIIS include the ease of data collection, high spatial and temporal resolution, and the nadir view of the canopy for every data point. Maps of the nitrogen, vegetation, and water status indices were constructed at a 1-m resolution and 40 maps of the research area were constructed during the season. The collected data was of very high quality and was valuable for calibration and development of remotely sensed indices.

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